

## CHAPTER TWELVE

# UCGIS Emerging Research Theme: Ontological Foundations for Geographic Information Science

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### 12.1 INTRODUCTION

Ontology has gained increased attention among researchers in geographic information science in recent years, and in the present paper we argue that ontology can play an important role in establishing robust theoretical foundations for geographic information science in the future. The growth of interest in the topic of geospatial ontology is documented by such activities as: a well-attended session on ontology at the 2000 AAG meeting in Pittsburgh, organized by Nadine Schuurman and David Mark, chaired by Max Egenhofer, and featuring presentations by Michael Curry, Greg Elmes and Harvey Miller, as well as by Schuurman and Mark. EuroConference on Ontology and Epistemology for Spatial Data Standards in LaLonde-sur-Mer, France, organized by Stephan Winter in September 2000 (<http://www.geoinfo.tuwien.ac.at/events/Euresco2000/gdgis.htm>); a special issue of the *International Journal of Geographical Information Science* appeared, containing papers from the EuroConference by Frank, Kokla and Kavouras, Kuhn, Raubal, Smith and Mark, and Worboys, all of which are listed in the references below. Several sessions and papers on ontology at the first International GIScience Conference held in Savannah, Georgia in October 2000 (<http://www.giscience.org>); and a number of recent awards by the National Science Foundation and the National Imagery and Mapping Agency, including Kuipers (1995), Egenhofer (1999), Findler and Malyankar (1999), and Mark and Smith (1999).

## **12.2 THE MEANING OF “ONTOLOGY”**

The term “ontology” has been used in philosophy and information systems in a number of ways. We provide here a brief discussion of some of the issues surrounding the use of the term, drawing especially on Guarino and Giaretta (1995) and on Smith (in press). Three main senses of the term can be distinguished, corresponding to the three main types of ontological research:

1. Ontology as a branch of philosophy deals with “the nature and the organisation of reality” (Guarino and Giaretta, 1995). Ontology in this sense seeks primarily to establish the types of entities that reality contains and to establish how these entities are related. The philosophical ontology of the geospatial domain would deal with the totality of geospatial objects, categories, relations, and processes—and with their interrelations at different resolutions.

2. Ontology in the information systems sense is defined as “a logical theory which gives an explicit, partial account of a conceptualization” (Guarino and Giaretta, 1995; compare Smith and Welty 2001). Note that, in contrast to the philosophical sense of the term, where ‘ontology’ is a mass noun that cannot be pluralized, in this information science sense one can speak of several ontologies.

3. Ontology, when conceived as a process of eliciting ontologies from different sorts of human subjects, is best understood as a branch of psychology. It involves the use of standard psychological methods in order to establish the conceptual systems that people use in relation to given domains of objects. This latter aspect of the ontology research domain has implications for geographic information science especially as concerns issues of usability.

For present purposes, the opposition between I and II is especially important. I can also be characterized as a conception of ontology as a *theory of reality*, by analogy with any other scientific theory, though specializing primarily in the preparation of *taxonomies* of the types of entities existing in a given domain (including, again, the types of relations which unify these entities together into complex wholes of different sorts). II can be characterized as a conception of ontology as a second-level theory relating to the first-level theories about reality or, more generally, to the various “conceptualizations” embraced by human beings for particular scientific and non-scientific purposes. Additionally, ontological research in sense I is pure or basic research carried out with the aim of increasing human knowledge, where ontological research in sense II is directed toward applications in the design of information systems and databases.

### 12.3 ONTOLOGICAL COMMITMENT

The philosopher Quine (1953) plays an especially important role in any consideration of the relations between the philosophical and information systems senses of the term “ontology,” and it is almost certainly through the channel of Quine’s influential paper “On What There Is” (1953) that the term first entered into the literature of artificial intelligence and then of information systems science.

For Quine, ontology studies the theories of the natural sciences, which he takes to be our best sources of knowledge as to what reality is like. Quine’s aim is to find the ontology *in* science. Ontology for him comes down to the study of the *ontological commitments* of, or in other words of the ontological presuppositions underlying, different natural-scientific theories. Each natural science has its own repertoire of types of objects to the existence of which it is committed. For Quine this is defined by the repertoire of predicates used by the corresponding theory in its canonical formalization in first-order predicate logic (the logic of quantifiers). Quine’s famous criterion of ontological commitment he formulated in the slogan: To be is to be the value of a bound variable. This might be interpreted in practical terms as follows: to determine what the ontological commitments of a scientific theory are it is necessary to determine the values of the quantified variables used in the canonical formalizations of its theories.

Information scientists have extended Quine’s understanding of ontology, using the term to refer not just to the taxonomies of entities accepted by given theories of natural science, but also to the taxonomies associated with, for example, standardized lexica or databases, or with enterprise management systems. They seek to establish what the users of given information processing systems are *committed to* as a result of their underlying conceptualizations. Thus ontology in the information systems sense seeks canonical descriptions of knowledge domains and associated classificatory theories. In such fields as artificial intelligence and computer science, ontology typically refers to a vocabulary or classification system that describes the concepts operating in a given domain through definitions that are sufficiently detailed to capture the semantics of that domain. It has been applied almost exclusively not to the large and messy worlds of natural scientific investigation but rather to the relatively controlled worlds of databases and information systems, or geographic subsystems that are heavily regulated, such as ship navigation (Malyankar, 1999, 2001), or highway codes and driving regulations (Kuhn, 2001).

To see why the project of an ontology in either the traditional philosophical sense or the Quinean sense has been embraced by so many influential figures in the information systems community, it is useful to point to what we might call the Tower of Babel problem as this arises in the database domain. Each of the many different groups of database system designers has its own idiosyncratic terms and concepts by means of which it builds frameworks for information representation; methods must be found to resolve the terminological and conceptual incompatibilities, which then inevitably arise. While such incompatibilities were initially

resolved on a case-by-case basis, it was recognized that the provision, once and for all, of a common terminological standard—a shared taxonomy of entities—could provide significant advantages over case-by-case resolution. The term “ontology” has come to be used by information scientists precisely to describe a canonical reference taxonomy of this sort.

## **12.4 OBJECTIVES**

“Ontological Foundations for Geographic Information” has been recognized as an emerging research theme by the University Consortium for Geographic Information Science (UCGIS). Under this umbrella, we unify several interrelated research subfields, each of which deals with different perspectives on geospatial ontologies and their roles in geographic information science. While each of these subfields could be addressed separately, we believe it is important that ontological research be carried out in a unitary, systematic fashion. Three broad sets of foundational issues need to be resolved: (i) conceptual issues concerning what would be required to establish an exhaustive ontology of the geospatial domain, (ii) representational and logical issues relating to the choice of appropriate methods for formalizing ontologies, and (iii) issues of implementation regarding the ways in which ontology ought to influence the design of information systems.

An integrated approach is necessary, because there is a strong interdependency between the methods used to specify an ontology, and the conceptual richness, robustness and tractability of the ontology itself. But such integration comes only at a price. For while the potential advantages of ontology for the purposes of information management are obvious, the task of providing a common reference ontology (a single consistent and stable set of category labels) which would be sufficiently rich to contain all the major taxonomical concepts used in all scientific disciplines is, even when we restrict ourselves to the spatial sciences, so enormous as to be unachievable without considerable compromises along the way.

We can understand the sorts of difficulties that can arise, if we consider that such an ontology, if it is to be widely accepted, must be neutral across different data communities. But there is, as experience has shown, a formidable trade-off between this constraint of neutrality and the requirement that an ontology be maximally wide-ranging and expressively powerful—that it should contain canonical definitions for the largest possible number of terms. One solution to this problem is the idea of a top-level ontology, which would confine itself to the specification of such highly general (domain-independent) categories as: time, space, inherence, instantiation, identity, measure, quantity, functional dependence, process, event, attribute, boundary, etc. (See for example <http://suo.ieee.org>.) The top-level ontology would then be designed to serve as a common, neutral backbone, which would then be supplemented by the work of ontologists working

in more specialized domains on, for example, ontologies of geography, or climatology, or ecology.

Our choice as to the framework of formal representation of ontology will have implications when it comes to information system implementations, and the latter will themselves serve as testbeds for the purpose of establishing the correctness and completeness—and usability—of the ontologies developed. None of the current UCGIS research priorities provides such an integrative perspective, and the topic of “Ontological Foundations for Geographic Information Science” is unique in this respect.

## **12.5 THE UCGIS APPROACH**

UCGIS will coordinate research in this area. Coordination is required because of the multiplicity of research communities involved. Work on geographic concepts, categories, relations, and processes from a theoretical perspective must be coordinated with geospatial data and software standards efforts on the one hand and with general (top-level) ontology projects on the other. The formal approaches in ontology will augment the process of laying down robust data and software standards in different sub-fields.

Ontology in the philosophical sense is an enterprise that cross-cuts all branches of science and information systems. This is because all sciences and information systems deal, in some way and at some level of generality, with reality. There then comes into play what we might call the ontologist’s credo (Smith, in press): *to create effective representations it is an advantage if one knows something about the things and processes one is trying to represent.*

Ontological *commitments*, on the other hand, underlie all forms of cognition. Hence, ontology in the information systems sense—ontology as the making precise of conceptualizations and commitments—is needed to support research in spatial information science insofar as the latter relates to how humans, both experts and non-experts, use and understand geospatial software and theories in spatial science. Ontology as the study of ontological commitments is thus close to the research issues dealt with by geographic information science under headings such as data modeling and representation.

Geospatial cognition and geographic information systems each relates in its own way to the spatial aspects of the real world, more specifically to the domain of objects and processes located in large spatial regions on or near the surface of the Earth. This latter domain exists independently of human cognition and concepts (even roads and cities, once built, enjoy an independent existence). The geospatial domain is in this respect contrasted, for example, to the domain targeted by banking information systems, where the objects and processes involved are themselves to a large degree constructs of the very systems humans build.

Spatial reality existed even before human beings entered the scene. The independence of the geospatial domain is made especially clear when we reflect

that—again in contrast to the banking case—there are several independent branches of natural science—geology, geomorphology, pedology, climatology, oceanography, ecology, forestry, and perhaps even geography itself—that deal with the same reality as that which is targeted by geographic information systems. This independence implies, however, that the philosophical and the information systems conceptions of ontology are much more closely allied in the geographic domain than in some other domains.

The task of ontology building does not focus on the design of specific algorithms and data structures that would allow implementation and coding of geospatial information and processes. Rather it aims to build robust, comprehensive and usable taxonomies. On this basis it seeks appropriate representations for geospatial phenomena to match the underlying reality, especially insofar as this reality is salient to human beings. Ontology of the geospatial domain is not a subset of the original ten UCGIS research challenges, although several of them addressed ontological issues. The ontology topic certainly has close relations to the representations topic, the scale topic, and to the conceptual or semantic aspects of the interoperability topic.

## **12 .6 THE IMPORTANCE OF THE EMERGING THEME TO NATIONAL RESEARCH NEEDS/BENEFITS**

It is widely recognized that the semantics of geospatial information is critical for the development of interoperable geospatial data and software. It is also widely recognized that GIS software and technology should be able to interoperate with other software and databases such as those involved in wireless applications, e-commerce, logistics, environmental health, and health care delivery. Such interoperability requires a common or shared ontology for the phenomena under consideration—any phenomena distributed over part or all of the Earth’s surface. This means also that research in the ontology of geospatial phenomena should be coordinated with efforts designed to establish geospatial terminology standards.

### **12.6.1 Priority Research Areas**

Serious research on the ontology of geographic phenomena has begun only recently, and thus far the work has been directed primarily toward the formal modeling of the geospatial world as this is experienced and conceptualized by non-experts (Smith and Mark 2001). An exhaustive ontology of the geospatial domain would be vast, and given the complex interrelations between the different spatial sciences will likely never be finalized. More reachable objectives would be to develop a complete upper-level ontology for the geospatial domain, and to develop in stepwise fashion detailed ontologies for subdomains, ontologies that are consistent with this upper-level ontology. Subdomains of highest priority

would be the principal domains of GIS application, together with areas of environmental and social science where GIS has been under-utilized due to ontological mismatches between the corresponding domains of objects and GIS software.

Since the geospatial sciences deal with phenomena across a variety of scales, a common ontology for the geospatial domain must relate to the entities addressed not only in common-sense spatial reasoning but also in scientific, engineering and computational representations of geospatial phenomena. Above all, it must provide a framework within which all of these types of representation can be integrated.

The ontology of the geospatial domain will define taxonomies of the different types of geographic objects, fields, spatial relations and processes. It will be accompanied by translation algorithms, mapping the ontology into the basic data models and representations necessary for scientific computing about geographic phenomena. The ontology will be formalized through axioms and definitions of classes, relations, and functions.

A need for formalized ontological frameworks for data integration has been recognized by many disciplines that specialize in the gathering and exchange of information. However, this need has received much less attention from scientists themselves. This is because, within each discipline or field of study, a shared conceptual system is normally ensured through the education and training of the scientists involved. Where cross-disciplinary communication and collaboration is required, however, ontology provides the needed common integration platform. Different environmental and social sciences share in common the fact that they study phenomena that occur or act over geographic space. Yet very little integration across these disciplines has taken place. The ontology of geospatial phenomena will provide the tools to support such integration and it will correspondingly facilitate the interoperability of the geospatial information systems addressing phenomena in these different fields.

### **12.6.2 Kinds of Ontological Research**

We have distinguished three types of ontology research, which must be regarded as complementary and mutually constraining, and which echo our distinction between three different senses of “ontology” above:

1. Research on ontology in the philosophical sense—ontology as theory of reality—which attempts to establish the types of objects, processes and relations, at different levels of scale and granularity, from out of which the geospatial domain is constituted. The methods employed here should be maximally opportunistic, involving (1) interaction with scientists from domains such as geology, climatology, and many others, designed to establish the sorts of entities populating their respective domains, and (2) the development of formal methods for integrating these populations of entities, for example in terms of part-whole

and granularity relations. At the same time, such research should be directed towards clarification of the relations between human knowledge, beliefs and representations on the one hand, the models and representations embedded in our data systems on the other hand, and the real world of objects beyond.

2. Research on the methods and tools for describing, accessing, comparing, and integrating geo-ontologies. This area falls into the standard information science mode, which means specifying the conceptualizations underlying different types of GISystems software and associated datasets for purposes of interoperability and cross-system translation.

3. Research in eliciting geo-ontologies from human subjects (both experts and non-experts) using standard psychological methods. This type of research is of importance in connection not only with usability issues but also with issues pertaining to observation error, data gathering and data-formulation.

The three types of ontological research are mutually constraining in virtue of the fact that we want our information systems to relate to the same real-world domain of objects as is captured (at different scales) in our scientific theories and in our everyday action and perception: geo-ontologies in every case take the same real, spatial world as their object, a world of constant change, of multifarious causal processes at different levels of scale and granularity. The underlying complexity of geo-ontological research is thus higher than standard ontological research in information systems, which relates primarily to the types of closed world models specified in database design and characteristically involves simplifications motivated by specific short-term pragmatic goals (Smith, in press).

### **12.6.3 Short-Term (2–3 Years)**

All UCGIS ontological research will involve formalization, and progress will be maximized if common formal-ontological tools and concepts are employed. A key short-term priority for research in this area is thus to develop and distribute an upper-level ontology for geospatial phenomena that can be used as a common framework to ensure that independently developed subdomain ontologies are consistent and interoperable. An early agreement on a formal language for specifying the ontology will contribute substantially to the potential to achieve longer-term goals. Again, consistency and interoperability with broader ontology projects is highly desirable. Thus, researchers in geospatial ontology should form links with general ontology projects such as the IEEE Standard Upper Ontology (SUO) Study Group (<http://ltsc.ieee.org/suo/index.html>), the work of LADSEB in Padua under the direction of Nicola Guarino (<http://www.ladseb.pd.cnr.it/infor/ontology/ontology.html>), and the GOL (General Ontological Language) project at the University of Leipzig (<http://www.ontologie.uni-leipzig.de/>). One medium-term project would be to study the family of formal mereotopological theories,

establish their properties, and refine the best ones for use in ontologies of the geospatial domain.

#### **12.6.4 Medium-Term (3–5 Years)**

Ontology-based wayfinding systems and agents (Sorrows and Hirtle, 1999; Raubal et al., 1997; Raubal, 2001) will provide a bridge between the data structures of a geographic information system and the users of the system. The conceptual hierarchy of a user is in many cases only partially related to structures used by an information system, which can result in abstruse or confusing directions. An important medium-term goal would be to provide a better understanding of the cognition of geographic concepts via the formalization of an ontology of naive geographical concepts (see Mark and Smith's recent work). We are making progress in this area, but need additional formalizations to develop further testable hypotheses.

Another important medium-term project would be research on the ontology of vagueness, following up on preliminary work on geographic objects with indeterminate boundaries reported in the book edited by Burrough and Frank (1996), and also in the various recent treatments of vagueness in geography by Varzi (in press), Bennett (2001) and Bittner and Smith (2001a).

An additional medium-term project would focus on the ontology of scale, and especially the issue of how to integrate spatial ontologies at different levels of granularity or resolution (Stell 2000, Bittner and Smith 2001a, 2001b, Smith and Brogaard 2001). Scale is another of the original UCGIS research priorities or challenges. The interaction between map scale, map resolution, and the level of detail that can be depicted on graphic maps was well known in cartography, but there are important differences in how size, scale, and resolution interact in digital representations.

Specification of the ontology of change (Galton 2001) and geographic process would be another medium-term priority; geographic objects such as lakes, rivers, and storm fronts have very special dynamic properties not studied in standard ontologies.

Yet another project would attempt to answer questions regarding the degree to which folk geographic concepts, such as clouds and storms, fronts and air masses, which are conceptualized as objects in folk and common-sense weather models, are useful, or even indispensable, in scientific models of atmospheric behavior. The ontology of meteorology is itself an important research area complementary to that of the projects here described.

Finally, the discipline of social ontology would attempt to establish the nature of geospatial objects in the institutional realm, including political objects such as states and nations and legal and economic objects such as real estate parcels and boundaries of coastal waters. (Bittner 2001, Smith 1995, Smith and Zaibert 2001, Frank 1997).

These ontological studies will need to be complemented by the development of appropriate methods and tools to describe ontologies. The development

of canonical languages for geo-ontologies is a medium-term project. Likewise, the development of computational methods to compare ontologies and to integrate them into web-based search engines is a medium-term research project.

#### **12.6.5 Long-Term (10 Years and Beyond)**

The long-term goal is to complete the description and formalization of the ontology of all phenomena at geographic scales, including those phenomena dealt with by other natural sciences such as climatology and oceanography. This needs to go hand-in-hand with the development of appropriate mechanisms that support the integration of geo-ontologies at different levels of explicitness, and the development of guidelines for the resolution of conflicts in geo-ontologies.

In addition, the development of geo-ontologies will complement other efforts underway, including the development of the semantic web (Hendler, 2001). The long-term goal of the semantic web project ([www.semanticweb.org](http://www.semanticweb.org)) is to build an extension of the WWW in which meaning is encoded through ontologies. The geo-ontologies will be a critical piece of the larger project designed to provide greater intelligence to the web.

### **12.7 EXAMPLE RESEARCH PROJECTS**

A good way to obtain examples of current research projects in geospatial ontology is to examine award abstracts from the National Science Foundation. A search of recent NSF awards relating to ontology on the NSF web site revealed 40 awards with some variant of 'ontology' in the award title or abstract. The fact that half of these are from the last three years is evidence of the emergent nature of ontology as a topic in information science. Of the 40 NSF awards, four mention geographic, spatial, or geospatial themes explicitly. We also mention below some additional projects funded by other agencies.

The project directed by Kuipers (1995), entitled "An Ontological Hierarchy for Spatial Knowledge", formalized the Spatial Semantic Hierarchy (SSH), a model for representations of spatial knowledge (Kuipers, 2000). This project, which ended in 1998, did not explicitly address spatial knowledge at geographic scales, and was mainly intended to support simulated and physical robots. The other three spatial ontology projects funded by NSF all began in 1999 and will extend from one to three years; all are focused on the geospatial domain. The fact that these funded projects were all initiated in 1999 is clear evidence that the topic is in an emerging phase, at least under the name "ontology".

Egenhofer's (1999) ontology project, entitled "NSF-CNPq Collaborative Research on Integrating Geospatial Information" involves collaboration with the Brazilian National Institute for Space Research (INPE), and focuses on semantic interoperability of spatial and geographic databases. Under the NIMA NURI project "Similarity Assessments Based on Spatial Relations and Attributes"

(<http://www.spatial.maine.edu/~max/nima.html>), this group is also designing computational methods to determine the similarity of different ontologies.

At the Pennsylvania State University, Mark Gahegan is working on “Enabling Collaboration and Improving Understanding: The Management of Semantics for Geospatial Information,” funded by a recent NIMA NURI award.

Findler and Malyankar (1999) were funded by NSF’s “Digital Government” program under the title “Digital Government: Representation and Distribution of Geospatial Knowledge”, a project to determine an ontology for coastal entities such as shorelines and tide tables, in partnership with the U.S. Coast Guard and NOAA (Malyankar, 1999, 2001).

Mark and Smith (1999) recently began a 3-year NSF-funded project entitled “Geographic Categories: An Ontological Investigation”, designed to determine the ontology of geographic objects and associated cognitive categories; the context of Mark and Smith’s project is general common-sense or naive geography, and the project emphasizes human subjects testing in a variety of languages. The results of the project are intended to contribute to spatial data transfer and semantic interoperability of general-purpose geographic software and data, and the work thus far has led to the clarification of a range of foundational and representational issues in geospatial ontology.

## **12.8 POSSIBLE SHOWCASE DEMONSTRATIONS**

The use of ontologies to facilitate retrieval from spatial databases can provide a visual demonstration of the possible outcomes of the research here described. The recent work of Egenhofer and his colleagues on sketched-based interfaces and the work of Sara Fabrikant on interfaces for spatial data suggest high-impact, portable demonstrations that can highlight the benefits of an ontological approach. Other demonstration projects may include the use of geospatial lexicons, for instance in intelligent web geo-services and advanced spatial similarity search engines. The application of methods for comparing computationally different ontologies will also lead to tools for comparing geospatial standards.

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